

FDNS CFD Code Benchmark for RBCC Ejector Mode Operation

James B. Holt
Marshall Space Flight Center
Huntsville, Alabama 35812

ABSTRACT

Computational Fluid Dynamics (CFD) analysis results are compared with benchmark quality test data from the Propulsion Engineering Research Center's (PERC) Rocket Based Combined Cycle (RBCC) experiments to verify fluid dynamic code and application procedures. RBCC engine flowpath development will rely on CFD applications to capture the multi-dimensional fluid dynamic interactions and to quantify their effect on the RBCC system performance. Therefore, the accuracy of these CFD codes must be determined through detailed comparisons with test data. The PERC experiments build upon the well-known 1968 rocket-ejector experiments of Odegaard and Stroup [1] by employing advanced optical and laser based diagnostics to evaluate mixing and secondary combustion. The Finite Difference Navier Stokes (FDNS) code [2] was used to model the fluid dynamics of the PERC RBCC ejector mode configuration. Analyses were performed for both Diffusion and Afterburning (DAB) and Simultaneous Mixing and Combustion (SMC) test conditions. Results from both the 2D and the 3D models are presented.

INTRODUCTION

The PERC RBCC test hardware is a single rocket two-dimensional design, see Figure 1, with variable geometry to enable studies of RBCC mixing and secondary combustion phenomena. Gaseous hydrogen and oxygen were used as rocket propellants with gaseous hydrogen injection at the end of the diffuser section for DAB testing. The sea level static configuration had a simple diverging two-dimensional inlet and exhausted to atmospheric pressure. Test measurements included wall static pressure, wall heat flux and overall thrust for rocket oxidizer-to-fuel (O/F) ratios of 4 and 8. Raman images taken during testing with a rocket O/F of 8 were used to obtain species mole fraction distributions for various stations downstream of the primary rocket to evaluate mixing and secondary combustion in the RBCC duct [3]. These measurements provide quality benchmark test data for CFD code validation. This paper compares the FDNS code results with the available benchmark test data.

APPROACH

The first set of analyses modeled the stoichiometric rocket (O/F=8) at 500 psia chamber pressure with fuel injection downstream of the rocket. Fuel is injected in the afterburner section of the RBCC duct where the rocket exhaust and the entrained air are completely mixed, DAB case. The second set modeled a fuel-rich rocket (O/F=4) at 500 psia chamber pressure with no downstream fuel injection. With a fuel-rich rocket chemical reactions and mixing begin simultaneously in the RBCC duct, SMC case. Run conditions for the FDNS simulations are given in Table 1.

-

All grids for the current analyses were generated with the software package Gridgen [4] using drawings supplied by PERC. The 2D model utilized a multizone grid with 42,270 grid points in the computational domain. Only half of the hardware flowpath was included in this domain due to hardware symmetry. Fuel ports were included in the 2D flowpath to account for downstream GH_2 injection in the $\text{O/F}=8$ run. A multizone 3D grid with 160,550 grid points was generated to remove the fuel injection ports from the flowpath and enable fuel injection from the sidewall. This domain models one quarter of the hardware flowpath and is coarse in the third direction, depth. All FDNS analyses were steady state and implemented finite-rate chemistry and thermodynamics with the standard $k-\epsilon$ turbulence model. The current chemistry model includes 7 species (H_2 , O_2 , H_2O , H , O , OH , and N_2) and 9 chemical reactions. N_2 is considered inert while all other species are considered to be reactive.

The primary rocket exit flow conditions for the DAB case were obtained from a previous detailed 3D analysis of the rocket geometry. For the SMC case, the exit conditions were obtained with the Chemical Equilibrium Combustion (CEC) code. In each case, the ejector mode analysis treats the rocket exit as a fixed inlet with the mass flow rate matching that of the corresponding PERC test. Additionally, the fuel injection ports in the DAB case were treated as downstream inlets. All walls are treated as no-slip adiabatic surfaces. A total pressure of one atmosphere is conserved on the far field freestream boundaries and symmetry conditions used along symmetry boundaries.

RESULTS AND DISCUSSION

Diffusion and Afterburning Case

FDNS calculated pressure and measured static pressure are compared in Figure 2. The 2D model predicts the test data trend but over predicts the pressure values. The higher values may be due to the flow blockage introduced by the fuel injection ports placed in the computational flowpath to simulation downstream H_2 injection. The coarse grid 3D model with the side port fuel injection produced results with pressure values in good agreement with the measured test data values.

Calculated entrained air predictions are shown in Table 2 along with the reported values from the PERC test. Air entrainment in both the 2D and 3D models was lower than the test values. The coarse 3D model predictions are farther from the test data than the 2D model. The lower air entrainment could be a result of the coarse grid in the depth along with the 2D topology used to model the test article inlet which does not adequately model the 3D flow entrainment in the inlet region.

H_2O , O_2 and N_2 mole fraction comparisons are shown in Figure 3 for four axial locations in the 3D FDNS model downstream of the rocket exit. For the first two axial locations the FDNS predictions are in very good agreement with the test data. Farther downstream the FDNS solution predicts less mixing of the rocket exhaust and the entrained air than seen in the test data.

Simultaneous Mixing and Combustion Case

FDNS pressure values for the SMC case are compared with the measured pressure along the upper RBCC duct wall in Figure 2. Again the 2D FDNS model predicts the correct pressure trend but the pressure values are too high. The coarse 3D model, as before, provides a much better prediction for the maximum pressure in the downstream section of the test article. Air entrainment comparisons for the SMC case were similar to those for the DAB case discussed earlier.

CONCLUSIONS

A review of the FDNS code benchmark study has been presented. 2D modeling of the PERC test article with the FDNS code provided the correct trends found in the test data. However, a 3D model was needed to match the test data values. FDNS predictions with even a coarse grid are in good agreement with axial pressure measurements and the species mole fraction measurements taken downstream of the primary rocket. Future modeling refinements include proper modeling of the air entrainment region and additional resolution in the third direction.

REFERENCES

- [1] Odegaard, E. A. and Stroup, K. E., "1966 Advanced Ramjet Concepts Program, Volume VIII-Ejector Ramjet Engine Tests- Phase I", The Marquardt Corporation, Technical Report AFAPL-TR-67-118, Volume VIII, January 1968.
- [2] Chen, Y. S., "FDNS - A General Purpose CFD Code, Version 4.0", Engineering Sciences, Inc., ESI-TR-97-01, Huntsville, AL., May 1997.
- [3] Lehman, M., Pal, S., Broda, J. C. and Santoro, R. J., "Raman Spectroscopy Based Study of RBCC Ejector Mode Performance," AIAA-99-0090, 37th AIAA Aerospace Sciences Meeting, Reno, NV, January 11-14, 1999.
- [4] Gridgen Version 13 user manual, <http://pointwise.com/>

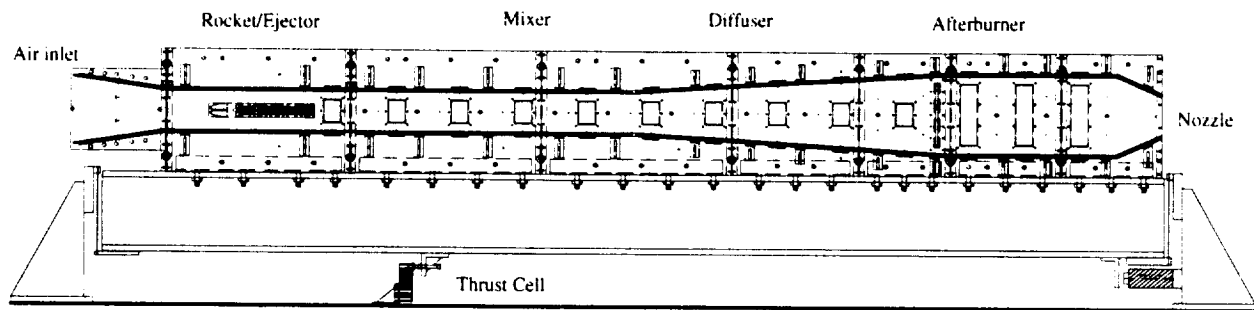


Figure 1. PERC RBCC Ejector Mode Experimental Hardware

Table 1 FDNS CFD Run Conditions

	DAB Case	SMC Case
Rocket O/F	8	4
Rocket GO_2 (lbm/sec)	0.6041	0.5231
Rocket GH_2 (lbm/sec)	0.0755	0.0654
Rocket P_c (psia)	500	500
GH_2 afterburner injection (lbm/sec)	0.0456	0.0000

Table 2 Calculated Entrained Air Values

O/F	PERC w_s/w_p	FDNS 2D w_s/w_p	FDNS 3D w_s/w_p
8	1.84	1.76	1.66
4	2.27	2.30	1.92

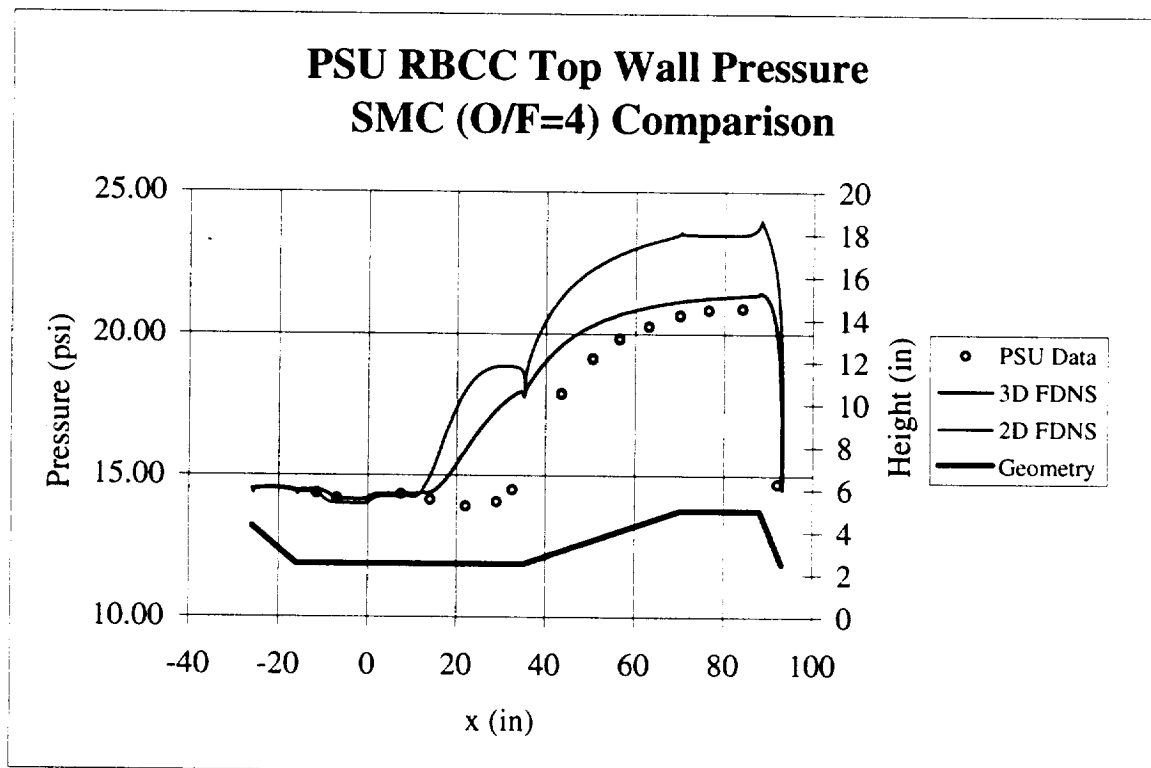
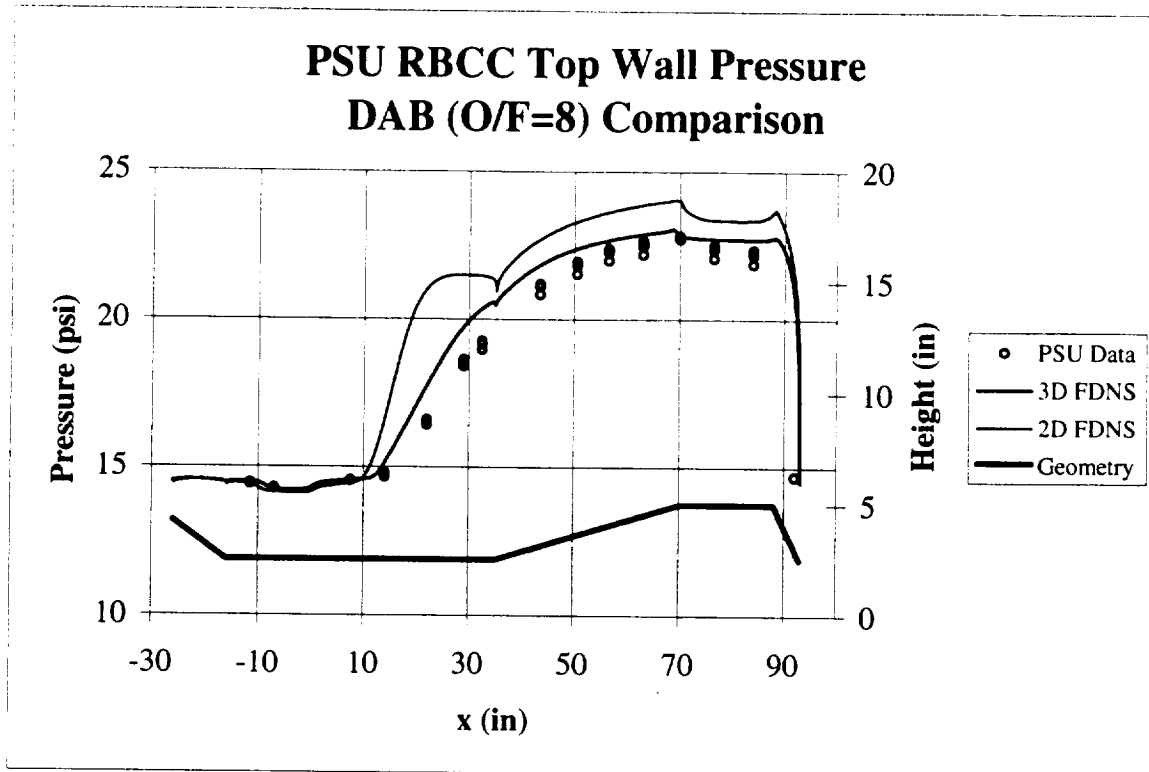


Figure 2. DAB Case Axial Pressure Comparison

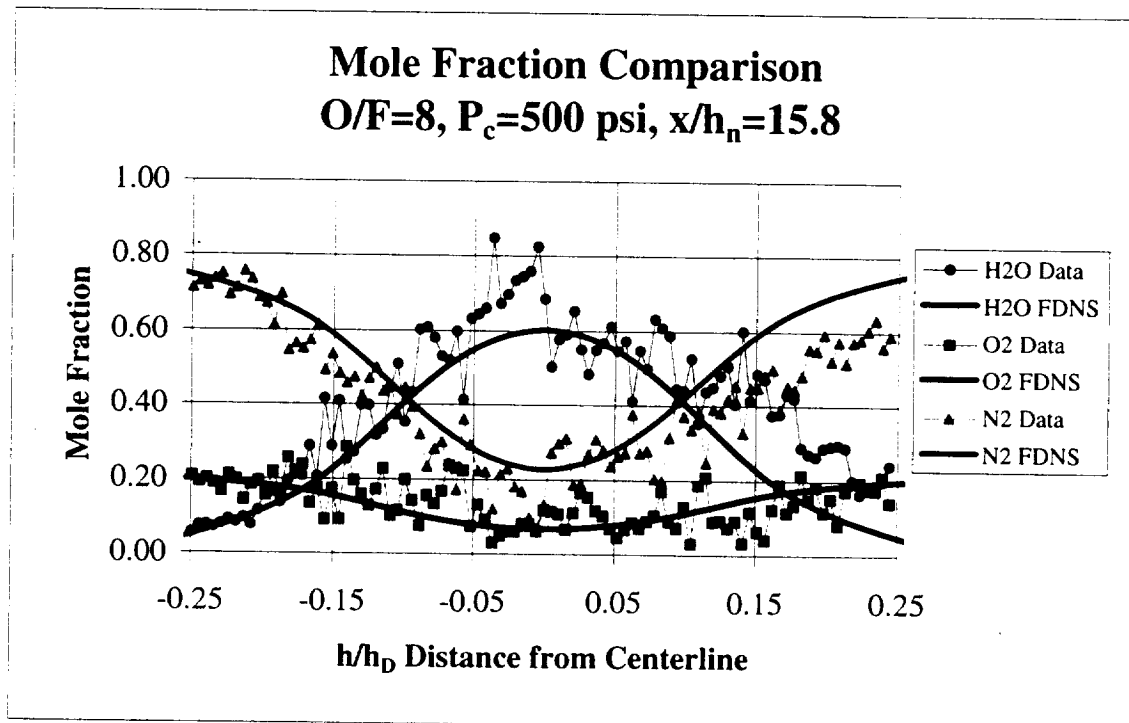
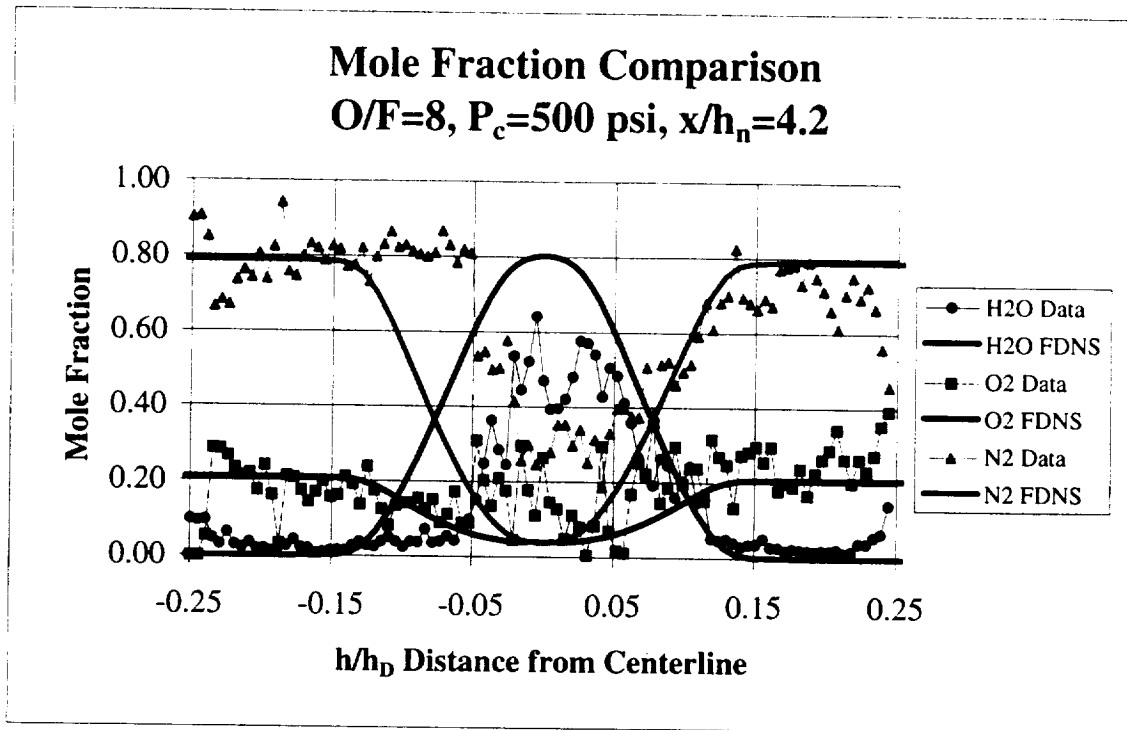


Figure 3. DAB Case Species Mole Fraction Comparison

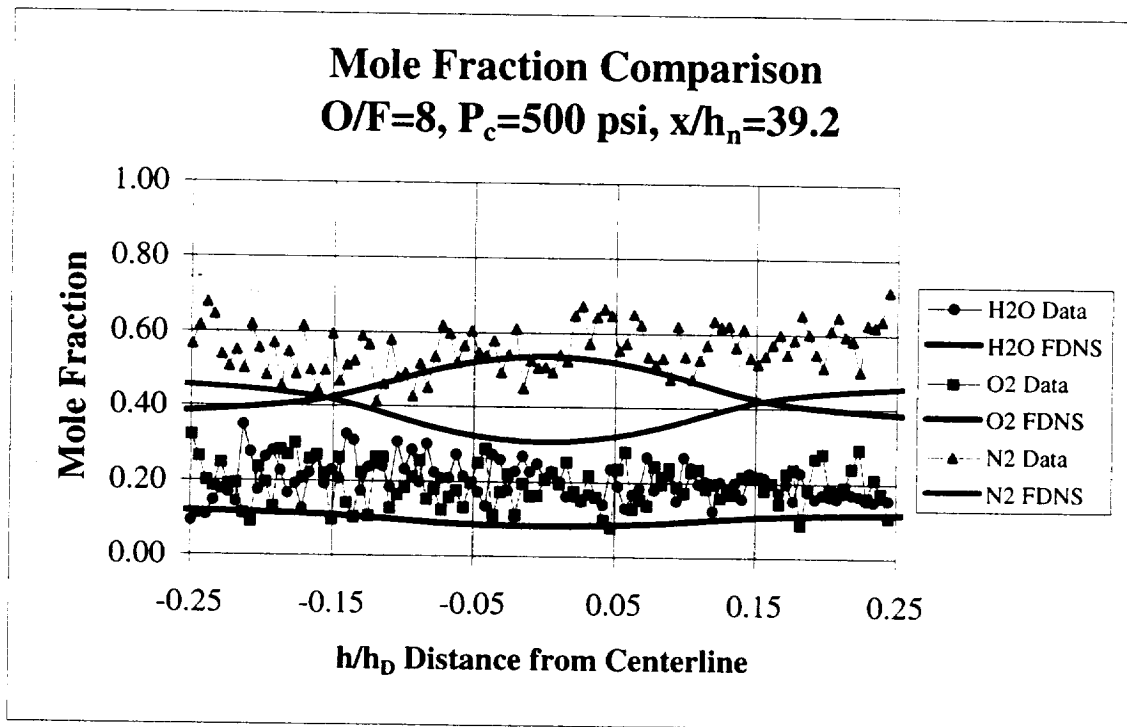
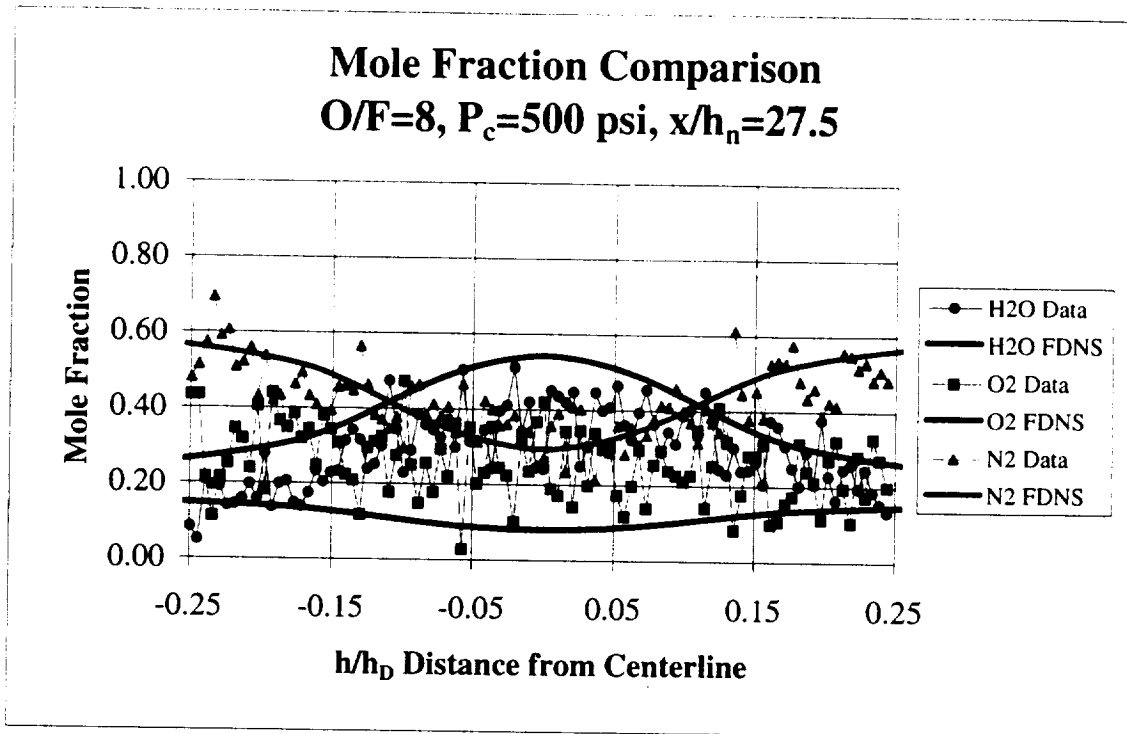


Figure 3 continued. DAB Case Species Mole Fraction Comparison